Resonant optical nonlinearity measurement of Yb\textsuperscript{3+}/Al\textsuperscript{3+} codoped optical fibers by use of a long-period fiber grating pair

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A new method of measuring optical nonlinearity for resonant nonlinear optical fibers is proposed. A long-period fiber grating (LPG) pair was used to measure the nonlinear refractive index $n_2$ of a Yb\textsuperscript{3+}/Al\textsuperscript{3+} codoped optical fiber, which was spliced between the two LPGs, as the fiber was pumped with a laser diode. The nonlinear refractive index of the Yb\textsuperscript{3+}/Al\textsuperscript{3+} codoped fiber near 1580 nm depended on the pump power. As the pump power increased, the nonlinear refractive index decreased. At launched pump powers of 2–8 mW, the nonlinear refractive index of the Yb\textsuperscript{3+}/Al\textsuperscript{3+} codoped fiber near 1580 nm was $7.5 \times 10^{-16}$ m\textsuperscript{2}/W. © 2002 Optical Society of America


Several measurement methods that incorporate pulse broadening,\textsuperscript{1,2} a Mach–Zehnder interferometer,\textsuperscript{3} or a twin-core fiber interferometer\textsuperscript{4} to determine the nonlinear optical (NLO) properties of optical fibers have been suggested and used. We propose a new method for measuring the optical nonlinearity of optical fibers by use of a simple measurement setup. A long-period fiber grating (LPG) pair was used as a sensor in the NLO measurement setup, together with a target fiber spliced between the two LPGs. It has been reported that the nonlinearity of an Yb\textsuperscript{3+} doped optical fiber near 1550 nm during optical pumping at 980 nm is much greater than that of silica glass fiber as a result of the Kramers–Kronig effect caused by changes in the absorption properties of ytterbium ions on laser pumping.\textsuperscript{5,6} The change in refractive-index of the fiber core is known to be related to the shift in wavelength that arises from interference between the core mode and the cladding mode of the fiber through the LPG pair.\textsuperscript{6,7} Thus the nonlinear refractive index of a resonant nonlinear optical fiber can be obtained from the shift of wavelength in the interference fringes on pumping with a laser diode (LD).

A schematic diagram of the measurement setup for resonant optical nonlinearity with a LPG pair is shown in Fig. 1. A nonlinear optical fiber of length $L_1$ is spliced between the two LPGs. If a light wave passes through the LPG pair, a transmission spectrum with interference fringes is formed as a result of the phase difference between the core mode and the cladding mode of the NLO fiber ($L_1$) and the LPG fiber ($2L_2$). The phase difference $\psi$ can be expressed as\textsuperscript{5}

$$\psi = (\beta_{\text{core}} - \beta_{\text{clad}}) (2L_2 - d) + (\beta_{\text{core}}^{\text{NLO}} - \beta_{\text{clad}}^{\text{NLO}}) L_1,$$

where $d$ is the length of the single LPG and $L_2$ is half of the LPG fiber length. $\beta_{\text{core}}$ and $\beta_{\text{clad}}$ are the propagation constants of the core and the cladding modes, respectively, in the LPG fiber. $\beta_{\text{core}}^{\text{NLO}}$ and $\beta_{\text{clad}}^{\text{NLO}}$ are the propagation constants of the core and the cladding modes, respectively, in the NLO fiber.

The interference fringes formed by the LPG pair can shift if there is a change in the refractive index of the core. When a beam pumped by a LD is launched into the core of the NLO fiber, a change in effective refractive index takes place with pump power, and this results in a shift of the interference fringes. Because the intensity of the pump beam decreases exponentially with increasing absorption through the NLO fiber, the amounts of effective refractive-index variation are different along the NLO fiber. The shift of the interference fringes represents the total phase shift induced by the effective index change of the core along the NLO fiber, satisfying the following equation based on the well-known coupled-mode theory:

$$\int_0^{L_1} \Delta n_{\text{core}}^{\text{NLO}}(z)dz = \frac{\lambda_p}{S} \Delta \lambda,$$

where $\Delta n_{\text{core}}^{\text{NLO}}(z)$ is the effective refractive-index change of the core at $z$, $\lambda_p$ is the wavelength of the fringe, $\Delta \lambda$ is the wavelength shift of $\lambda_p$, and $S$ is the fringe spacing.\textsuperscript{5} The phase change $\Delta \psi$ induced by the pump beam is related to the nonlinearity of the NLO fiber by the following equation:\textsuperscript{5}

Fig. 1. Schematic diagram of the setup for resonant nonlinearity measurement of nonlinear optical fiber by use of a LPG pair. WDMs, wavelength-division multiplexers; OSA, optical spectrum analyzer.

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\[
\Delta \psi (\lambda_p) = \frac{2\pi}{\lambda_p} \int_0^{L_1} \Delta n_{\text{core}} \text{NLO}(z) \, dz
\]
\[
\approx \frac{2\pi}{\lambda_p} n_2 L_{\text{eff}} 2b \frac{P_{\text{pump}}}{A_{\text{eff}}},
\]
(3)

where \(n_2, L_{\text{eff}}, \) and \(b\) are the nonlinear refractive index, the effective length of the NLO fiber, and the polarization-dependent parameter between the pump beam and the signal beam, respectively. \(P_{\text{pump}}\) is the pump power launched into the core of the NLO fiber, and \(A_{\text{eff}}\) is the effective core area. Therefore, from Eqs. (2) and (3), the nonlinearity (nonlinear refractive index) of the NLO fiber can be obtained from the following equation:

\[
n_2 = \frac{A_{\text{eff}}}{L_{\text{eff}} 2b P_{\text{pump}}} \frac{\lambda_p}{S} \Delta \lambda.
\]

Note that the measurable value of the nonlinear refractive index depends essentially on how small a wavelength shift \(\Delta \lambda\) can be measured and thus is limited by the resolution of the optical spectrum analyzer.

A LPG pair was fabricated upon a boron codoped germanosilicate glass fiber by use of a 200-µm-period amplitude mask to form interference fringes near 1580 nm. The fibers were hydrogen loaded at 100 °C at a pressure of 100 MPa for a week before the grating was written. After grating formation on the bare fiber by the KrF excimer laser (248 nm), the fibers were annealed at 100 °C for 24 h. Then Yb\(^{3+}/\text{Al}^{3+}\)-codoped germanosilicate glass fibers, which were manufactured by a solution doping technique with an alcohol solution of YbCl\(_3\) (0.1 M) and AlCl\(_3\) (0.5 M) for nonlinear optical application, were spliced between the two LPGs, as shown in Fig. 1. The core diameter of the Yb\(^{3+}/\text{Al}^{3+}\) codoped fiber, its absorption coefficient at the pump wavelength of 980 nm, and its cutoff wavelength were 4.3 µm, 0.294 cm\(^{-1}\), and 1.17 µm, respectively. The concentration of ytterbium ions in the fiber core was estimated to be \(\sim 850\) parts in \(10^6\). The total distance \(L\) between the two gratings of the LPG pair including the Yb\(^{3+}/\text{Al}^{3+}\) codoped fiber was 43 cm, and distance \(L_1\) (Fig. 1) was 33.2 cm. To examine the effect of the pump beam on the boron codoped germanosilicate glass fiber we also prepared a boron codoped fiber with the LPG pair \((L = 15\) cm). Then a wavelength-division multiplexer was used to multiplex and demultiplex the light signals at 980 nm and 1550 nm, respectively.

We monitored the wavelength shift of valley points of the interference fringes at 1575–1600 nm by changing the launched pump power of the LD (at 980 nm) from 0 to 13 mW. The resolution of the optical spectrum analyzer used in this study was 0.05 nm.

We measured the optical transmission of the Yb\(^{3+}/\text{Al}^{3+}\)-codoped NLO fiber with the LPG pair by increasing the LD pump power; the result is shown in Fig. 2. The interference fringes were found to shift toward the longer-wavelength side with the increase in pump power. Figure 3(a) shows the wavelength shifts of three fringes and the corresponding phase shifts near 1580 nm with the launched pump power, which were obtained from the measured data in Fig. 2 and expressions (2) and (3). For comparison, the phase shift estimated by a theoretical model\(^4\) is also shown in Fig. 3(a). The experimental results showed good agreement with the theoretical values at a pump

![Fig. 2. Transmission spectra near 1580 nm of the Yb\(^{3+}/\text{Al}^{3+}\)-codoped nonlinear optical fiber with the LPG pair on pumping with the LD at 980 nm.](image)

![Fig. 3. (a) Wavelength shift of the interference fringes and the corresponding phase shift, and the theoretical phase shift near 1580 nm with the pump power for the Yb\(^{3+}/\text{Al}^{3+}\)-codoped germanosilicate glass fiber. (b) Wavelength shift of the interference fringes for the boron codoped germanosilicate glass fiber.](image)
power of less than 3 mW, but the deviation gradually increased as the pump power increased. This result is attributed to the saturation of the absorbed pump power in the finite ytterbium-doped optical fibers because we calculated the theoretical values by assuming that the launched pump power would be completely absorbed in the ytterbium doped fiber. In the case of the boron doped fiber with the LPG pair shown in Fig. 3(b), however, the shift was negligibly small compared with that of the Yb$^{3+}$/Al$^{3+}$ codoped fiber with the LPG pair. Therefore, it is evident that the wavelength shift in the Yb$^{3+}$/Al$^{3+}$ codoped fiber can be attributed to the NLO property of the Yb$^{3+}$/Al$^{3+}$ codoped fiber. Wavelength shift $\Delta \lambda$ was found to increase with increasing pump power.

From the results in Fig. 3(a) and from Eq. (4) the nonlinear refractive index of the Yb$^{3+}$/Al$^{3+}$ codoped fiber was calculated. The effective area of the core was estimated to be 16.06 $\mu$m$^2$, and the polarization-dependent parameter was assumed to be 2/3, the value for conventional non-polarization-maintaining fibers. The calculated nonlinear refractive index $n_2$ with pump power is shown in Fig. 4. The nonlinear refractive index was taken as an averaged value of the data obtained from three peak wavelengths near 1580 nm, and its error bar was denoted as a range of $n_2$ calculated at three peak wavelengths. The error bar was large at a pump power of less than 1 mW but decreased as the pump power increased. Nevertheless, at a pump power of less than 1 mW the nonlinear refractive index of the Yb$^{3+}$/Al$^{3+}$ codoped fiber showed a maximum, which gradually decreased as the pump power increased. The nonlinear refractive index was found to be $1.37 \times 10^{-14}$ to $0.56 \times 10^{-14}$ m$^2$/W at pump powers of 0.3 to 13 mW, respectively.

The decrease in the nonlinear refractive index of the ytterbium doped fiber with the increase of the pump power is related to the origin of the nonlinearity in the Yb$^{3+}$/Al$^{3+}$ codoped fiber. The nonlinearity of the Yb$^{3+}$/Al$^{3+}$ codoped fiber is known to come from a population inversion of ytterbium ions by the optical pump at 980 nm and depends on the efficiency in the pumping of the ytterbium ion. Because the extent of the absorption increase of the pump beam in the ytterbium ions becomes smaller at higher pump power as a result of the increase of spontaneous emission in the excited state, the nonlinear refractive index of the Yb$^{3+}$/Al$^{3+}$ codoped fiber must decrease with increasing pump power.

In conclusion, a novel method for measuring the resonant optical nonlinearity of nonlinear optical fibers has been proposed. We estimated the nonlinear refractive index of Yb$^{3+}$/Al$^{3+}$ codoped fibers spliced with a LPG pair by measuring the wavelength shift of the interference fringes on LD pumping at 980 nm. The nonlinear refractive index was found to decrease with increasing launched pump power. At pump powers of 2–8 mW the nonlinear refractive index was $\sim 7.5 \times 10^{-15}$ m$^2$/W near 1580 nm.

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